GENERATING USER-DEPENDENT RSA KEYS

Related Applications

The present application is related to commonly assigned and concurrently filed United States Patent Application Serial No. _____, entitled "METHODS,

5 SYSTEMS AND COMPUTER PROGRAM PRODUCTS FOR GENERATING USER-DEPENDENT CRYPTOGRAPHIC KEYS," (Attorney Docket No. 5577-160) the disclosure of which is incorporated herein by reference as if set forth fully.

Field of the Invention

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The present invention relates to cryptography and more particularly to the generation of cryptographic key values for RSA asymmetric cryptosystems.

Background of the Invention

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Asymmetric (or public) key cryptosystems use two different keys that are not feasibly derivable from one another, one for encryption and another for decryption. A person wishing to receive messages, generates a pair

20 of corresponding encryption and decryption keys. The encryption key is made public, while the corresponding decryption key is kept secret. Anyone wishing to

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communicate with the receiver may encrypt a message
using the receiver's public key. Only the receiver may
decrypt the message, since only he has the private key.
Asymmetric-key cryptosystems may also be used to

5   provide for digital signatures, in which the sender
encrypts a signature message using his private key.
Because the signature message can only be decrypted
with the sender's public key, the recipient can use the
sender's public key to confirm that the signature

10   message originated with the sender. One of the best-
known asymmetric-key cryptosystems is the RSA, named
for its originators Rivest, Shamir and Adleman. One
version of RSA is defined by ANSI Standard X9.31-1998.

RSA is widely used in many cryptographic systems.

15   RSA gets its security from the difficulty of factoring
large prime numbers. The RSA public and private keys
are derived from two randomly selected large prime
numbers .

The general way to derive the two RSA keys is as

20   follows. First choose two random large prime numbers p
and q. Compute $N=p{\times}q$, which is referred to as the
public modulus. Then randomly choose the public key e
such that e and $(p\text{-}1){\times}(q\text{-}1)$ are relatively prime.
Finally, compute the private key d such that $d=e^-$

25   $^1\bmod((p\text{-}1){\times}(q\text{-}1))$. RSA encryption and decryption
formulas are straightforward. To encrypt a message m,
compute $c=m^e\bmod N$, where c is the ciphertext. To decrypt
c, compute $m=c^d\bmod N$.

It has been suggested that two users with

30   different moduli might have a common prime factor in

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their moduli, either by accident or because of a poor design (design flaw) in the system. If $N_1 = p_1 \times q_1$ and $N_2 = p_2 \times q_2$, where (say) $p_1 = p_2$, then it is easy to find p_1 or p_2 given N_1 and N_2 and , i.e., an efficient algorithm

5   exists to find the common factor p_1 or p_2 given N_1 and N_2. If such a common prime factor were to exist, and this fact were discovered, then it would also be an easy matter to factor each modulus into its prime factors. This, of course, would allow the private keys

10   to be computed from the corresponding public keys, and hence for the security of the keys to be compromised.

In general, mechanisms for differentiating between users are known. For example, a particular individual can be identified or verified through a user identifier

15   (such as a globally unique name) or biometric data (such as fingerprint, hand geometry, iris pattern, facial features, voice characteristics, handwriting dynamics, earlobe characteristics, etc.).

As is well known to those having skill in the art,

20   biometric information is one or more behavioral and/or physiological characteristics of an individual. Biometric identification and/or verification uses a data processing system to enable automatic identification and/or verification of identity by

25   computer assessment of a biometric characteristic. In biometric verification, biometric information is verified for a known individual. In biometric identification, biometric information for an individual is compared to known biometric information for many

30   individuals in order to identify the individual.

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Biometric identification/verification systems, methods and computer program products can measure one or more of the following behavioral and/or physiological characteristics of an individual:

5 fingerprint, hand geometry, iris pattern, facial features, voice characteristics, handwriting dynamics, earlobe characteristics and keystroke dynamics. Other biometric characteristics may be used. Applications using biometric technologies include biometric check

10 cashing machines, payment systems that substitute biometric data for personal identification numbers, access control systems that use biometric data, biometric employee time and attendance recording and biometric passenger control for transportation. Many

15 other applications may utilize biometric information for identification and/or verification. See the publications entitled *"Biometrics, Is it a Viable Proposition for Identity Authentication and Access Control"*, to Kim, Computers & Security, Vol. 14, 1995,

20 pp. 205-214; *"A Robust Speaker Verification Biometric"*, to George et al., Proceedings, the IEEE 29th International Carnahan Conference on Security Technology, Oct. 1995, pp. 41-46; *"On Enabling Secure Applications Through Off-line Biometric*

25 *Identification"*, to Davida et al., Proceedings of the IEEE Computer Society Symposium on Research in Security and Privacy, 1998, pp. 148-157; and *"Biometric Encryption: Information Privacy in a Networked World"*, to Brown et al., EDI Forum: The Journal of Electronic

30 Commerce, v. 10, No. 3, 1997, pp. 37-43. However, while biometric identification and user identification

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may allow for identification of users, these existing uses may not allow for authentication of the source of encryption keys.

In the above cited Davida *et al.* publication, in
5 Section 5.2, it was proposed that biometrics could be used with or as keys. However, Davida *et al.* assumes that the biometric information is secret information. Furthermore, Davida *et al.* may not work for any size key and describes a procedure which may not allow for
10 pre-computing information for generation of a key value. Furthermore, the proposal of Davida *et al.* may allow two users to generate the same key values and, thus, does not assure that the generated keys are disjoint.
15 In light of the above discussion, a need exists for improvements in the generation of encryption keys for RSA cryptosystems.

Summary of the Invention

20 In view of the above discussion, it is an object of the present invention to provide cryptographic keys which may be authenticated.

A further object of the present invention is to provide for the generation of cryptographic keys which
25 may be audited to determine the user which generated the cryptographic keys.

A further object of the present invention is to provide RSA keys which satisfy the requirements of the ANSI Standard X9.31-1998.

Yet another object of the present invention is to provide RSA keys which are disjoint for different users.

These and other objects of the present invention may be provided by methods, systems and computer program products which generate an RSA cryptographic key by obtaining user specific information about a user and determining a user specific range of values based on the user specific information. The potential range of RSA prime values is divided into at least two subintervals and the user specific range of values mapped onto a first of the at least two subintervals. A first user-dependent RSA prime is then selected from the range of RSA prime values in the first subinterval corresponding to the mapped user specific range of values.

Furthermore, the user specific range of values may also be mapped onto a second of the at least two subintervals where the second subinterval is different from the first subinterval. A second user-dependent RSA prime may then be selected from the range of RSA prime values in the second subinterval corresponding to the mapped user specific range of values.

By mapping a user specific range of values onto the potential range of prime values, the present invention will guarantee a very high probability that different users will select prime values from different ranges. Thus, the range of prime values from which an RSA prime is selected may be used to authenticate and audit the prime after generation. If a prime is not from the user specific range mapped onto the range of

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potential prime values, then the key value was not from the user corresponding to the user specific information. Such a mapping into at least two different subintervals may also assure that two users

5   will not have the same primes and that the two primes will be from different subintervals of the range of potential prime values.

In a further embodiment, a specific range of values are linearly mapped onto a first of the at least

10   two subintervals. In a still further embodiment of the present invention, the user specific range of values onto the first subinterval and the second subinterval utilizing the same mapping function.

In particular embodiments of the present invention

15   the RSA primes comprise n bits and the at least two subintervals comprises RSA prime values from the set

$[\sqrt{2}(2^{n-1}), 2^{n-1}+2^{n-3/2}]$ and the second subinterval

comprises RSA prime values from the set

$[2^{n-1}+2^{n-3/2}, 2^{n}]$. Furthermore, the difference between

20   the first RSA prime and the second RSA prime is greater than 2^{n-2}.

In yet another embodiment of the present invention, the first subinterval is an interval [a,b], the user specific range is an interval [c,d] and the

25   linear mapping function is the function defined by,

$$F(x) = ux + v \text{ , where } u = \frac{d-c}{b-a} \text{ and } v = \frac{bc-ad}{b-a} \text{ .}$$

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In another embodiment of the present invention, a second RSA prime is selected from the potential range of RSA prime values.

In particular embodiments of the present
5   invention, the user specific information is biometric information, a globally unique user identification or a combination of the two.

In another embodiment of the present invention, the first user-dependent RSA prime is selected by
10   selecting a random point in the range of RSA prime values in the first of the at least two subintervals corresponding to the mapped user specific range of values and then utilizing the random point as a starting point for a search for a prime number (p) in
15   the range of RSA prime values in the first of the at least two subintervals corresponding to the mapped user specific range of values. Furthermore, it may be determined if a candidate for p is considered outside the range of RSA prime values in the first of the at
20   least two subintervals corresponding to the mapped user specific range of values. A new random point is then selected as a search starting point if a candidate for p is considered outside the range of RSA prime values in the first of the at least two subintervals
25   corresponding to the mapped user specific range of values. The search for p would then be restarted utilizing the new random point.

In yet another embodiment of the present invention, a cryptographic value corresponding to a
30   source entity is generated by obtaining entity specific information associated with the source entity. The

cryptographic value is then selected from a range of
cryptographic values based on the entity specific
information, where the range of cryptographic values
based on the entity specific information is disjoint
5   with ranges of cryptographic values associated with
entity specific information associated with entities
other than the source entity. In particular
embodiments, the entity specific information may be
biometric information, a globally unique user
10   identification or a company identification.

In a further embodiment, where the cryptographic
value comprises an RSA prime, the selection of the RSA
prime may be accomplished by selecting the RSA prime
from a portion of the range of potential RSA prime
15   values based on the entity specific information. The
portion of the range of potential RSA prime values is
defined by mapping an entity specific range of values
onto the range of potential prime values.

In a still further embodiment of the present
20   invention, the source entity of the cryptographic value
may be authenticated by determining if the
cryptographic value is within the range of
cryptographic values based on the entity specific
information associated with the source entity.

25   Thus, the present invention may provide for
"branding" a cryptographic value so that the
cryptographic value may be authenticated by determining
if the value corresponds to a unique range of values
associating with an entity through the use of entity
30   specific information, such as a company identification

or such a the user specific information of biometric or
user identification information.

As will further be appreciated by those of skill
in the art, the present invention may be embodied as
5   methods, apparatus/systems and/or computer program
products.

Brief Description of the Drawings

Figure 1 is diagram of a data processing system
10   suitable for use with the present invention;

Figure 2 is a detailed view of a data processing
system suitable for use with the present invention;

Figure 3 is a flowchart illustrating operations
according to a fourth alternative embodiment of the
15   present invention; and

Figure 4 is a flowchart illustrating
authentication/auditing of a branded value according to
one embodiment of the present invention;

Figure 5 is diagram illustrating the division of
20   the key space and the assignment of user specific
subspaces for an RSA encryption technique according to
the present invention; and

Figure 6 is a flowchart illustrating operations
according to one embodiment of the present invention.

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Detailed Description of the Invention

The present invention now will be described more
fully hereinafter with reference to the accompanying
drawings, in which preferred embodiments of the
30   invention are shown. This invention may, however, be
embodied in many different forms and should not be

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construed as limited to the embodiments set forth
herein; rather, these embodiments are provided so that
this disclosure will be thorough and complete, and will
fully convey the scope of the invention to those

5 skilled in the art. Like numbers refer to like
elements throughout.

The present invention can be embodied as systems,
methods, or a computer program products for generating
a user-dependent RSA cryptographic primes and keys

10 which are unique. As will be appreciated by those of
skill in the art, the present invention can take the
form of an entirely hardware embodiment, an entirely
software (including firmware, resident software, micro-
code, *etc.*) embodiment, or an embodiment containing

15 both software and hardware aspects. Furthermore, the
present invention can take the form of a computer
program product on a computer-usable or computer-
readable storage medium having computer-usable or
computer-readable program code means embodied in the

20 medium for use by or in connection with an instruction
execution system. In the context of this document, a
computer-usable or computer-readable medium can be any
means that can contain, store, communicate, propagate,
or transport the program for use by or in connection

25 with the instruction execution system, apparatus, or
device.

The computer-usable or computer-readable medium
can be, for example but not limited to, an electronic,
magnetic, optical, electromagnetic, infrared, or

30 semiconductor system, apparatus, device, or propagation
medium. More specific examples (a nonexhaustive list)

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of the computer-readable medium would include the
following: an electrical connection having one or more
wires, a portable computer diskette, a random access
memory (RAM), a read-only memory (ROM), an erasable

5 programmable read-only memory (EPROM or Flash memory),
an optical fiber, and a portable compact disc read-only
memory (CD-ROM). Note that the computer-usable or
computer-readable medium could even be paper or another
suitable medium upon which the program is printed, as

10 the program can be electronically captured, via, for
instance, optical scanning of the paper or other
medium, then compiled, interpreted, or otherwise
processed in a suitable manner if necessary, and then
stored in a computer memory.

15   Referring now to **Figure 1**, an exemplary embodiment
of a computer system **30** in accordance with the present
invention typically includes input devices **32**, such as
a keyboard or keypad **31**, a microphone **42** and/or
preferably, a biometric information input device **35**.

20 The computer system **30** also preferably includes a
display **34** and a memory **36** that communicate with a
processor **38**. The computer system **30** may further
include a speaker **44** and an I/O data port(s) **46** that
also communicate with the processor **38**. The I/O data

25 ports **46** can be used to transfer information between
the computer system **30** and another computer system or a
network (*e.g.*, the Internet). **Figure 1** also
illustrates that computer system **30** may include a
storage device **40** which communicates with memory **36** and

30 processor **38**. Such a storage device may be any type of

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data storage device as described above. These
components are included in many conventional computer
systems (*e.g.*, desktop, laptop, or handheld computers)
and their functionality is generally known to those

5   skilled in the art.

Furthermore, while the present invention is
described with respect to the computer system **30**, as
will be appreciated by those of skill in the art, the
present invention may be incorporated into many other

10 devices where RSA cryptographic primes and/or keys are
generated and, thus, may comprise an embedded function
in many other devices. Thus, the present invention
should not be construed as limited to use in computer
systems such as illustrated in **Figure 1** but may be

15 incorporated in any device having sufficient processing
capabilities to carry out the operations described
below.

Figure 2 is a more detailed block diagram of the
computer system **30** that illustrates one application of

20 the teachings of the present invention. The processor
38 communicates with the memory **36** via an address/data
bus **48**. The processor **38** can be any commercially
available or custom microprocessor or other processing
system capable of carrying out the operations of the

25 present invention. The memory **36** is representative of
the overall hierarchy of memory devices containing the
software and data used to implement the functionality
of the computer system **30**. The memory **36** can include,
but is not limited to, the following types of devices:

30 cache, ROM, PROM, EPROM, EEPROM, flash, SRAM, and DRAM.

As shown in **Figure** 2, the memory 36 may hold four
major categories of software and data used in the
computer system 30: the operating system 52; the
application programs 54; the input/output (I/O) device
5   drivers 58; and the data 56. The I/O device drivers 58
typically include software routines accessed through
the operating system 52 by the application programs 54
to communicate with devices such as the input devices
32, the display 34, the speaker 44, the microphone 42,
10   the I/O data port(s) 46, and certain memory 36
components.   The application programs 54 comprise the
programs that implement the various features of the
computer system 30 and preferably include at least one
application module or object for RSA key generation 60
15   which carries out the operations of the present
invention as described below. Finally, the data 56
represents the static and dynamic data used by the
application programs 54, operating system 52, I/O
device drivers 58, and any other software program that
20   may reside in the memory 36.   As illustrated in **Figure**
2, the data 56 preferably includes a secret seed value
70 and biometric or other user specific data 72.
Additional intermediate data (not shown) may also be
stored in memory.   Furthermore, while the present
25   invention is described as an application executing on
computer system 30, as will be appreciated by those of
skill in the art, the present invention may be
implemented in any number of manners, including
incorporation in operating system 52 or in an I/O
30   device driver 58.

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The present invention will now be described with respect to **Figures 3, 4** and **Figure 6**. **Figures 3, 4** and 6 are flowchart illustrations of embodiments of the present invention. It will be understood that each

5   block of the flowchart illustrations, and combinations of blocks in the flowchart illustrations, can be implemented by computer program instructions. These program instructions may be provided to a processor to produce a machine, such that the instructions which

10 execute on the processor create means for implementing the functions specified in the flowchart block or blocks. The computer program instructions may be executed by a processor to cause a series of operational steps to be performed by the processor to

15 produce a computer implemented process such that the instructions which execute on the processor provide steps for implementing the functions specified in the flowchart block or blocks.

Accordingly, blocks of the flowchart illustrations

20 support combinations of means for performing the specified functions, combinations of steps for performing the specified functions and program instruction means for performing the specified functions. It will also be understood that each block

25 of the flowchart illustrations, and combinations of blocks in the flowchart illustration, can be implemented by special purpose hardware-based systems which perform the specified functions or steps, or combinations of special purpose hardware and computer

30 instructions.

The present invention provides for generating RSA cryptographic primes and/or keys using user specific information such as users' user identification (userID) data as well as users' biometric data. While userID

5   data and biometric data are fundamentally different, the two data types have characteristics in common which may be exploited in providing user-dependent cryptographic primes and/or keys. For example, some of the differences in userID and biometric data can be

10 identified as follows:

1)   A userID is assigned to a user, whereas biometric data is obtained or derived from the user. Generally speaking, a user's userID is an independent variable, whereas a

15   user's biometric data is a dependent variable.

2)   A user's userID can be changed. A user's biometric data cannot be changed. At most, a user can attempt to switch from one biometric

20   to another biometric (e.g., fingerprint to hand geometry).

3)   Generally, the set or space of user identifiers may be dense, making it feasible to enumerate the set of user identifiers.

25   Generally, the space of user biometric data is not dense, making it infeasible to enumerate the biometric data for each user.

4)   Biometric data can be used to authenticate a user while userID data cannot be used to

30   authenticate a user.

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5)   A userID is a constant. User biometric data
      is not constant.

However, the similarities in userID and biometric
data which may be utilized to provide user-dependent
cryptographic keys can be identified as follows:

1)   A userID is different for each user and
      biometric data is generally different for
      each user. Note that, in some cases, it may
      happen that the biometric data for one user
      overlaps (in whole or in part) with another
      user. The degree to which this may occur can
      depend on a combination of the biometric
      method being employed and the sensitivity of
      the biometric reader devices being employed.

2)   A userID data is non-secret data. Biometric
      data should be considered as non-secret data,
      although in some vendor proprietary systems
      user biometric data is encrypted (i.e.,
      protected). Since there is no practical way
      to prevent the capture of user biometric data
      outside the biometric system, it is false to
      assume that the secrecy of user biometric
      data can be maintained over time.

3)   Biometric data, like userID data, can be used
      to identify users. In fact, in some sense,
      biometric data offers a better mechanism for
      user identification, since biometric data
      provides a mechanism of positive
      identification, whereas userID data, until
      verified via a separate authentication

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protocol, is only representative of a claimed
identity.

One potential advantage to using biometric data as
the user specific information is that with biometric
5   data, there is potentially an easy mechanism for the
user to prove their identity, especially if the user
carries their biometric certificate on a portable token
(*e.g.*, smart card). With a userID, the presumed or
claimed identity of the user is known, however, the
10   user to whom the key or cryptographic variable belongs
will not necessarily have an easy means to prove that
they are that user. A user will not always carry
sufficient credentials to prove their identity (*e.g.*,
birth certificate or passport).

15   **Figure 3** illustrates an embodiment of the present
invention which guarantees that two different users
will generate different cryptographic values. As seen
in **Figure 3**, the space of all potential cryptographic
values (*i.e.* 2^n for an n-bit cryptographic value) is
20   divided into 2^b subspaces where b is the number of bits
of user specific information and where n > b (block
300). Note that each of the 2^b subspaces contain
cryptographic values having n bits. One of the
subspaces is then selected based on the user specific
25   information of a particular user (block **302**). The
user-dependent cryptographic value is then selected
from the subspace selected by the user specific
information (block **304**). Optionally, the selected
value may be further mixed (block **306**) utilizing a
30   mixing function, such as a 1 to 1 mixing function

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described in Matyas, M., Peyravian, M., Roginsky, A., and Zunic, N., "Reversible data mixing procedure for efficient public-key encryption," Computers & Security Vol. 17, No. 3, (265-272) 1998, which can be applied to

5 any arbitrary n-bit input.

As an example, a way to divide an n-bit space into 2^b sub-spaces is to take the first b bits from the user specific information and allow the remaining n-b bits to take any value (e.g. concatenating a random value of

10 n-b bits with the b bits of the user specific information). The b-bit user specific data may include a t-bit field which indicates the type of biometric data (e.g., fingerprint, hand geometry, iris pattern, facial features, etc.).

15 If the operations illustrated in **Figure** 3 are terminated at block **304**, the generated value is, in general, highly structured. In this case, the generated n-bit cryptographic value consists of a user-specific portion of b bits (e.g., biometric data) and a random

20 secret portion of $n-b$ bits. If the user-specific portion is a userID, then the user-specific portion would be a non-secret constant value for each user. If the user-specific portion is biometric data, then the user-specific portion might still be non-secret and

25 contain structure or redundancy. In either case, it could be undesirable for a cryptographic value to contain so much predictability in some particular portion of it which might give an attacker some advantage. Thus, it may be advantageous to employ a

30 mixing function to mix the user-dependent value so that

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the secret entropy in it will be uniformly spread over the entire key or random number.

As illustrated in optional block **306** of **Figure 3**, the n-bit key or random value produced is subjected to a further mixing operation. The n-bit key or random value, produced using the above scheme, is mixed using a 1-to-1 mixing function to produce the final value. One such suitable 1-to-1 mixing function is the reversible data mixing function described above which can be applied to any arbitrary n-bit input.

The specification of the b bits of user-specific information can be further explained, and amplified on. In certain cases, the values of n and b will be specified or fixed. In that case, the length of the user-specific information L may be less than b (L<b), equal to b (L=b), or greater than b (L>b). If L=b, then the entire user-specific information is used as the desired b bits. If L<b, then the desired b bits can be obtained as a function of the user-specific information, e.g., by tiling the user-specific information and selecting the first b bits from the tiled user-specific information. If L>b, then b bits can be obtained as a function of the user-specific information, e.g., by hashing the user-specific information by selecting b specific bits of Z where Z = H(B)||H(B+1)||H(B+2)||...||H(B+a), where a is the largest number smaller than h/b, where h is the number of bits resulting from the hash function H and where || represents a concatenation operation.

While the present invention does not guarantee that the same user will not accidentally generate the

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same primes as RSA key values, if the user saves all prior moduli, it could be readily determined if the newly generated primes are factors of any previously generated moduli. Such testing would be up to the user, and totally under the user's control, both to save prior moduli and test these moduli. The really difficult and insurmountable problem would be to test one user's primes against the moduli for all other users. The present invention obviates the need for such testing.

Another benefit of the utilization of the present invention, is that by making the cryptographic value generation process dependent on user-specific data, such as a userID or biometric data, one has the ability to later prove that a generated value belongs to a particular user. In this regard, the present invention provides a means to "brand" a value so that its rightful user can be determined. This branding feature may ensure that a user can prove that a cryptographic value is one belonging to, or generated in, his designated space of values and that a user cannot deny that a value is one belonging to, or generated in, his designated space of values.

Figure 4 illustrates operations according to a further embodiment of the present invention which utilizes the branded value to authenticate the source of the value. As seen in **Figure 4**, the branded value is received (block **400**) and entity specific information (such as the user specific information described above) is recovered from the received branded value. The branded value is preferably a value which has been

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generated in a manner described above according to the
various embodiments of the present invention utilizing
the user specific information to provide the branded
value. After recovering the entity specific

5   information, this information is then utilized to
determine the source of the branded value (block **404**).
Preferably, the recovery and evaluation are performed
by determining if the received value is a value from
the subspace of the source. If such is the case, then

10 the source of the branded value is authenticated.

Utilizing the above characteristics of userIDs and
biometric data, the present invention may provide for
the generation of RSA cryptographic primes and keys as
described in **Figure 6**. **Figure 6** will be described with

15 reference to **Figure 5** which is an illustration of the
mapping operations of the present invention to provide
user-dependent RSA primes from the interval of
potential primes for an n bit prime. As seen in **Figure
6**, the present invention provides for generating user-

20 dependent RSA primes which are unique by obtaining user
specific information of b bits (block **200**). The
interval of potential RSA prime values is then divided
into two intervals (block **202**)(illustrated in **Figure 5**
as I_1 and I_2). An interval based on the user specific

25 information (d_U of **Figure 5**) is then mapped to each of
the two intervals I_1 and I_2, preferably with a linear
mapping function to provide h_{U1} and h_{U2}, which are the
images of d_U in the intervals I_1 and I_2 (block **204**).

After mapping the user specific interval to the

30 two intervals, each interval is utilized to provide one

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of the two primes used in RSA (p and q). Thus, the flowchart of **Figure 6** provides two paths from block **204** which may be executed concurrently or sequentially. A first path from block **204** selects a start point sp_1 for

5 a search for the p RSA prime in the interval h_{U1} (block **206**). A search is then performed from the start point sp_1 in the interval h_{U1} to determine the p RSA prime (block **208**). When a candidate for the p RSA prime is found it is determined if the candidate falls within

10 the h_{U1} interval (block **210**). If not, then a new start point is selected at random from the h_{U1} interval and the search process begins again. If the candidate p RSA prime is within the interval h_{U1}, then the candidate is used as the RSA prime p.

15 A second path from block **204** selects a start point sp_2 for a search for the q RSA prime in the interval h_{U2} (block **207**). A search is then performed from the start point sp_2 in the interval h_{U2} to determine the q RSA prime (block **209**). When a candidate for the q RSA

20 prime is found it is determined if the candidate falls within the h_{U2} interval (block **211**). If not, then a new start point is selected at random from the h_{U2} interval and the search process begins again. If the candidate q RSA prime is within the interval h_{U2}, then the

25 candidate is used as the RSA prime q.

Thus, the present invention can provide RSA primes which are based on user specific information. These primes may then be further used to generate user-dependent RSA key values as described above.

30 Furthermore, because the intervals d_U for users are

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disjoint, the resulting RSA primes will also be
disjoint. By making the prime generation process
dependent on user-specific data, such as a userID or
biometric data, one has the ability to later prove that
5   a generated prime and/or key belongs to a particular
user. In this regard, the present invention can provide
a means to "brand" a key or prime so that its rightful
user can be determined. This branding feature may
ensure that a user can prove that a key or prime is one
10   belonging to, or generated in, their designated space
of keys or primes and that a user cannot deny that a
key or prime is one belonging to, or generated in,
their designated space of keys or primes.

In a public key cryptosystem, consider the case
15   where an adversary steals another user's private key,
and then takes the public key and requests and receives
a certificate for that public key from a certification
authority (CA). In this case, the certificate binds
the public key to the adversary's userID. The
20   adversary then signs with the stolen private key.
Later the adversary, repudiates their signatures by
claiming that the other party stole their private key.
However, the branding of the present invention can
defend against the described attack. If a dispute
25   arises, the branded key will indicate which user is the
authorized user.

In case of a dispute, the user-specific
information in the branded key, prime or other
cryptographic value is used to determine the identity
30   of the user to whom the value belongs. If the user-
specific data is a userID, then the identity of the

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user is automatically known. If the user-specific data
is biometric data, then the biometric data may be used
to establish the identity of the user, using a
biometric identification process. The process of
5   biometric identification consists of comparing the
given biometric data against a set of biometric
templates, *e.g.*, a set of biometric templates stored in
a central data base. We assume that for each such
biometric template there is an associated userID
10   identifying the user to which the template pertains.
If a "match" is found, then the identity of the user
has been determined.

However, if it were the case that the presumed
identity of the user is given, then a biometric
15   verification procedure could be used instead. If the
biometric data stored in the key or cryptographic
variable were a biometric template, then the user could
be asked to provide a biometric sample, thus enabling
the user to authenticated against the given biometric
20   template. If the biometric data stored in the key,
prime or other cryptographic value were instead a
biometric sample, then the biometric sample would have
to be authenticated against a biometric template (for
that user), *e.g.*, a biometric template stored in a
25   central data base or a biometric template contained in
a trustworthy biometric certificate that itself could
be validated.

The present invention is particularly well suited
for use in RSA prime and key generation which satisfies
30   the ANSI standard. According to ANSI standard X9.31-
1998, the generation of an RSA key begins by

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generating a random number in an appropriate interval. This number, in turn, serves as a starting point for a search for a prime number which then becomes a part of the secret key. Hence it is not sufficient to

5   guarantee that every user gets a different starting point in this process. It is the chosen primes that should ultimately be different.

While sharing one prime between two different users does not immediately lead to a breakdown of an

10   RSA encryption or signature generation, it may lead to various attacks if the fact that the primes are shared gets discovered. The identical primes can be generated accidentally or can be deliberately set equal by an attacker whose job is to generate the keys for the RSA

15   algorithm. It is difficult to guard against such an attack, because the public keys $N_1=pq_1$ and $N_2=pq_2$ are different and it is not known how to check if one of the primes, p, is the same without examining every pair of public keys.

20   Second, some primes are more secure than others and, therefore, it is important to make sure that they are not only unique, but also not deliberately chosen to be weak by a user, even within user-specific data constraints. Such choice of primes would constitute

25   what is known as "the first party attack."

The present invention can satisfy all of the requirements of RSA key generation outlined in the ANSI standard and, in addition, can guarantee that all of the primes generated by different users are unique and

30   are ultimately tied to user-specific data which may provide audit and authentication capabilities.

In the description of the ANSI compliant
embodiment of the present invention, the user-specific
data (*i.e.*, userID or biometric data), denoted by *B*, is
uniquely expressed by *b* bits. When the user-specific
5   data is biometric information, either the "biometric
sample" taken in real-time or the pre-computed
reference "biometric template" of a user may be
utilized. In either case it is assumed that the
biometric data is constant. Biometric data need not be
10 secret. It is further preferred that the *b* bits allows
for expressing any fuzziness included in the biometric
data, if biometrics are used as the user-specific data.

As described above, the objective is to generate
two random *n*-bit long (where *n*>*b*) prime numbers *p* and
15 *q*, using the user-specific data *B*. As is further
described above, this may be accomplished by first
dividing the *n*-bit long random number space into 2^b sub-
spaces. Each sub-space is assigned to a particular
user based on their *b*-bit unique user-specific data.
20 Then, *n*-bit long random numbers from the user's sub-
space.

The user's sub-space is mapped to two intervals of
the potential key values utilizing, preferably, a
linear function. Thus, throughout this section the
25 present invention will be described with reference to a
linear function *F(a,b,c,d;x)* that maps an interval
[a,b] into an interval *[c,d]*. When it is clear from
the context what parameters are used the *x* and also the
a, b, c and *d* may be omitted from the formula for *F*. *F*

can be defined explicitly as $F(x) = ux + v$, where $u = \dfrac{d-c}{b-a}$

and $\quad v = \dfrac{bc - ad}{b-a}$.

In order to generate a prime pair (p, q) for a particular user U with user-specific data B, we first

5   allocate the following interval of 2^{n-b-1} numbers for U. These will be all numbers whose binary representations contain n bits, with the first bit set to 1, followed by b bits of U's user-specific data B. The remaining $n-b-1$ bits can take any values. This interval

10 therefore contains 2^{n-b-1} consecutive integers and all of these numbers are greater than or equal to 2^{n-1} and smaller than 2^n. The intervals are all distinct, since no two users share the same user-specific data B. An interval created using U's user-specific data will be

15 denoted d_U and is illustrated in **Figure 5**, and the entire interval $[2^{n-1}, 2^n]$ will be called D.

While, U's primes p and q could be selected from this interval, there are, however, two requirements of the ANSI standard that may not allow this. First, both

20 p and q must be greater than $\sqrt{2}\,(2^{n-1})$. This is

required so that the RSA public key $N=pq$ has exactly $2n$ bits. Second, the difference between p and q must be large, which might not be possible (depending on the value of $n-b$) if they were both selected from the same

25 interval.

Therefore, the interval $I = [\sqrt{2}(2^{n-1}), 2^n]$ is

divided into two intervals of equal lengths:

$$I_1 = [\sqrt{2}(2^{n-1}), 2^{n-1} + 2^{n-3/2}] \quad \text{and} \quad I_2 = [2^{n-1} + 2^{n-3/2}, 2^n] \quad .$$

Then the interval D is mapped onto I_1 using the linear

5   function F defined above with parameters a, b, c and d

representing the end points of the corresponding

intervals. As is seen in **Figure 5**, h_{Ux} represents the

corresponding image of interval d_U mapped to interval

I_x. The points of both intervals can be viewed as real

10   numbers. All of the h_{U1} subintervals of I_1 are

disjoint. The length of each of these subintervals is

$$\frac{length(d_U) \times length(I_1)}{length(D)} = 2^{n-b-1}(1 - \frac{1}{\sqrt{2}}) \quad , \text{ which is}$$

approximately 0.293 of the lengths of the original

intervals d_U.

15   Next, as is described in **Figure 6** at block **206**, a

random point sp_1 is selected in h_{U1}. The selection may

be performed by any mechanism that allows for passing

an audit where the randomness of this selection could

be demonstrated. This mechanism could be a properly

20   adopted scheme from the ANSI standard or any other

agreed-upon procedure. Then a prime number p is

generated precisely as described in ANSI Standard

X9.31-1998, with sp_1 being the starting point for a

search of p. As is described in blocks **208** and **210** of

25   **Figure 6**, if the search for p continues until a

candidate is considered outside h_{U1}, the search stops
and a new starting point sp_1 must be selected randomly.

As described above with reference to **Figure 6**, the
prime q may be generated exactly like p, except that
the interval D is mapped onto the interval I_2 rather
than onto I_1. This procedure guarantees that q-p is
larger than the difference between the length of I_1 and
the length of h_U. It may be demonstrated that this
difference is greater than 2^{n-2} for every $b\geq1$, so the
requirement of the ANSI Standard X9.31-1998 for p and q
to be sufficiently far apart is easily satisfied. The
user then can publish its public key $N=pq$ (along with a
public exponent e).

It may also be shown that the intervals h_U are
large enough for a search for a prime number to be
successful under reasonable assumptions on n and b. A
first assumption is that $n\geq512$, $i.e.$, the prime numbers
p and q are at least 512 bits long (the shortest value
of n permitted by ANSI standards). A second assumption
is that b is less than or equal to about 200. While
this second assumption may not be true for any possible
kind of biometric measurements, there are fewer than 2^{33}
human beings living on Earth and, therefore, while the
biometric measurements are expected not to be precise
and having 33 bits would not be enough to create a
unique template for every living person, 200 bits
should be more than sufficient. Under these
assumptions, the length of every interval h_U is greater
than $0.29 \times 2^{512-200-1} > 2^{309}$.

The point sp_1 is chosen uniformly randomly in the interval h_U. With probability $1-2^{-20}$ there will be at least 2^{289} integers in h_U greater than sp_1. As it is specified in ANSI Standard X9.31-1998, the prime number

5   p must have a certain remainder $v(\text{mod } r)$, where r is equal to either $p_1 p_2$ or $8 p_1 p_2$, and p_1 and p_2 are prime numbers that guarantee that the generated prime p is "strong." Each of the primes p_1 and p_2 has at least 100 but no more than 120 bits in its binary representation,

10   so $r \leq 2^{243}$. Hence with probability $1-2^{-20}$ there will be at least 2^{46} integers in h_{U1} greater than sp_1 and having the desired remainder $v(\text{mod } r)$. The density of primes among them is greater than $1/ln(2^{n-1})$, so if n=512, then on the average, one out of every 355 consecutive

15   integers in the corresponding numerical sequence will be prime. More than half of these primes will be mutually prime with the RSA public exponent e. This results in a very high probability of finding the desired prime p in the interval h_U. In the unlikely

20   event that sp_1 is chosen too close to the upper bound of h_{U1}, so that an appropriate prime within h_{U1} can not be found, a search starts over with a new randomly generated point sp_1. If the desired size of the RSA primes is larger, say, 1024 bits, then the user-

25   specific data can have many more bits of data and still allow for the generation of RSA keys.

Utilizing the present invention, a potential attacker may possess the knowledge of the tighter bounds on the possible values of p and q than in the

30   general scheme ANSI Standard X9.31-1998 which does not

guarantee that the keys are unique and tied to user-specific data. However, if the tight bounds are known for p, then this knowledge combined with the knowledge of the public key N yields approximately the same range for the possible values of q that the knowledge of U's user-specific data would provide. In any case, the attacker has to deal with large primes coming from an interval of length at least 2^{309}, and may be difficult, if not impossible, for one to take advantage of this knowledge.

While the present invention has been described with respect to a particular preferred embodiment, as will be appreciated by those of skill in the art, alternative methods may also be employed while still benefitting from the teachings of the present invention. For example, prime number q could be taken from anywhere in the interval I_2. This would still make the RSA public key $N=pq$ unique for each user, since no two users could have the same p. No user will be able to claim that their keys were generated by somebody else since no other user-specific data could lead to the generation of this p.

Another possible alternative embodiment would be to map D into I_2 using some function other than the function used to map D into I_1. This would make it possible for one user to have a larger p but a smaller q than the corresponding primes that another user might generate. Alternatively, mapping functions other than linear mapping functions may be utilized, however, it

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is preferred that whatever mapping function is utilized that the images h_U are disjoint.

The present invention has also been described with reference to the use of user specific information.
User specific information could be a userID or, biometric information or a combination of the two. In this regard, the present invention provides a means to "brand" a key, prime or other cryptographic value so that its rightful user can be determined. Those skilled in the art will recognize that such branding is not limited to only users, but could be used to brand a key, prime or other cryptographic value with information specific to and associated with an entity where the entity is other than a human user (*i.e.* entity specific information). For example, the user specific information could be used to brand information with a company identifier (companyID), thus enabling one to show that the branded value belongs to a specific company. Whereas a biometric is associated with a specific user, an identifier could be associated with a user, group, organization, company, etc., and therefore the present invention is not limited to a method of branding based only on user specific information. Thus, as used herein the term user specific information may also refer to entity specific information. A human user is just an example of one type of entity.

In the drawings and specification, there have been disclosed typical preferred embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only

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and not for purposes of limitation, the scope of the invention being set forth in the following claims.